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An Automatic Bias Control (ABC) Circuit for Injection Lasers

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A totally electronic method of stabilizing the output light of an injection laser is presented. This novel method compensates the drift of the threshold current in gallium aluminum arsenide lasers by means of a feedback signal derived from the laser voltage.

I. INTRODUCTION

The threshold current of an injection laser varies from device to device and is a function of the device age and temperature. This threshold variation causes the laser output to change when the drive current is held constant. One must therefore provide a bias control circuit to compensate for the threshold variations.

Feedback circuits using photodetection have been successfully used for this purpose.[1] The output is monitored with an optical detector and compared with the input signal to generate an error signal that is fed back into the laser current.

This paper introduces a new concept of compensating the change in the laser threshold by using the electrical characteristics of junction lasers. An electrical circuit monitors the ac voltage and the ac current of the laser and generates the bias current needed to operate the laser above the threshold level independently of the laser temperature and age.

One of the benefits of using an electronic feedback scheme to stabilize the laser output is the elimination of an optical detector; this reduces the number of optical components required and may lead to a more economical and simpler solution than using a photodetector.

The electronic bias control method is based on the fact that the laser junction voltage saturates at currents above threshold.[2–8] Figure 1 shows L and V_j as functions of I. L is the laser output light at one of the faces, V_j is the laser junction voltage, and I is the laser current. Figure 1 also shows the changes in L and V_j produced by varying I in the vicinity of the laser threshold, I_t. The laser current is the sum of a bias current I_b

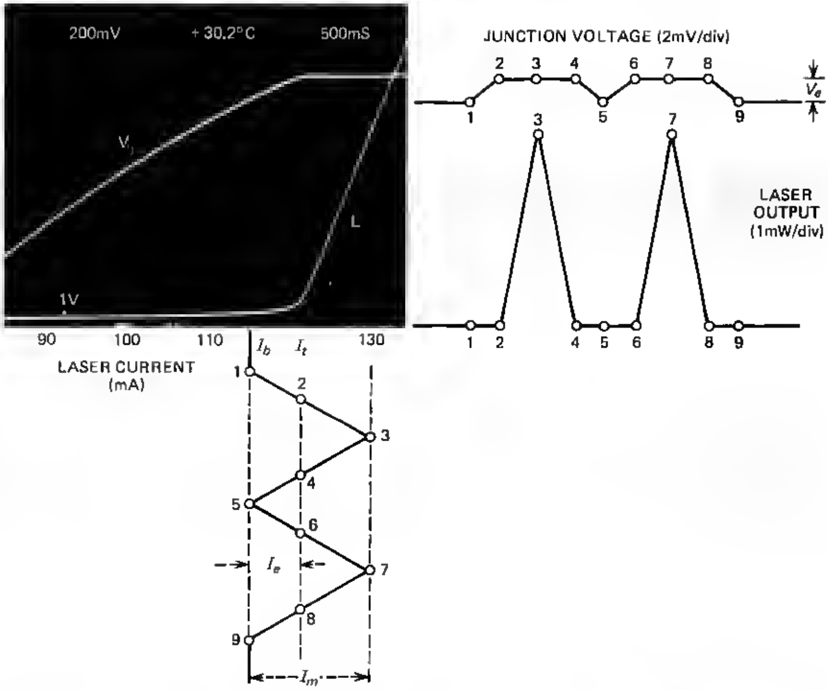

Fig. 1—Laser junction voltage and laser output light as a function of the laser current.

and a modulated current I_m. The part of I_m below I_t (called I_e) is an error current that does not modulate L but modulates V_j by a magnitude V_e. Conversely, the part of I_m above I_t modulates L but not V_j.

Laser stabilization consists of monitoring the junction voltage and increasing the laser bias current until the junction voltage is saturated. This is achieved automatically and continuously by an electronic circuit called an Automatic Bias Control (ABC) circuit. The ABC circuit monitors the laser voltage, generating an error signal proportional to the degree that the laser junction voltage is not saturated, and increases the bias current in the laser until the error voltage is minimized. The ABC circuit consists of an operational amplifier that amplifies the error voltage, a peak envelope detector that rectifies the amplifier output, and a current source that produces the current to bias the laser.

The circuit shown in Fig. 2 was built to study some of the characteristics of the electronic feedback method proposed here. Without stabilization provided by this circuit, the light output L of an injection laser varies strongly with temperature, as shown in Fig. 3 by the curve labeled "without feedback." Here, a constant bias of 124 mA was supplied, and the laser was modulated with a 70-kHz, 5-mA sinusoidal signal. One sees

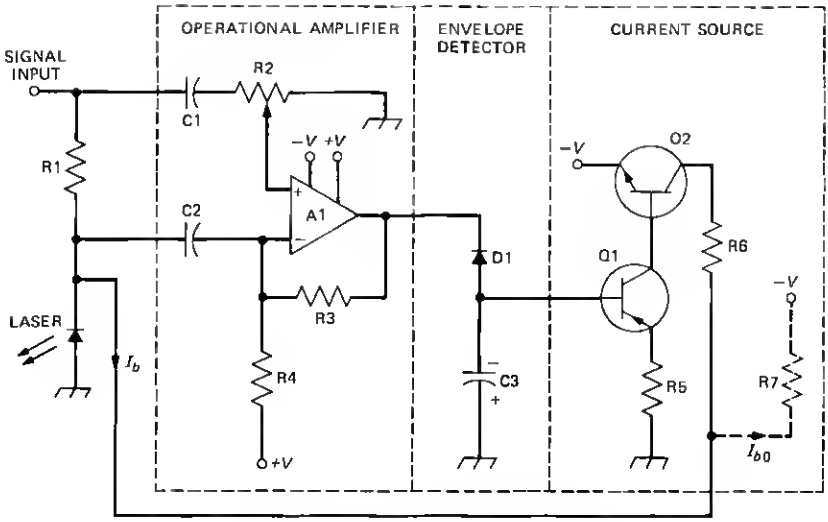

Fig. 2—Automatic bias control circuit.

immediately from the other curve, labeled "with feedback," how use of the ABC circuit improves the output stability. The variation $\Delta L/\Delta T$ is reduced from 0.37 mW/°C to 0.023 mW/°C, a factor of 16.

The following sections cover the details of the functioning and the limitations of the ABC circuit.

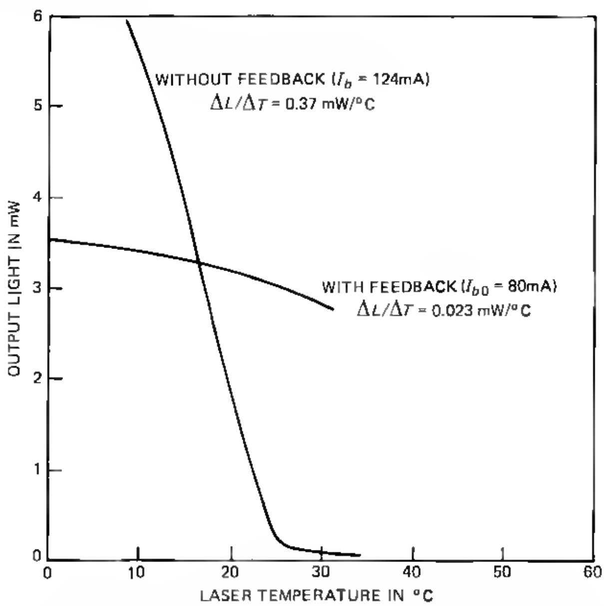

Fig. 3—Laser output as a function of the laser temperature.

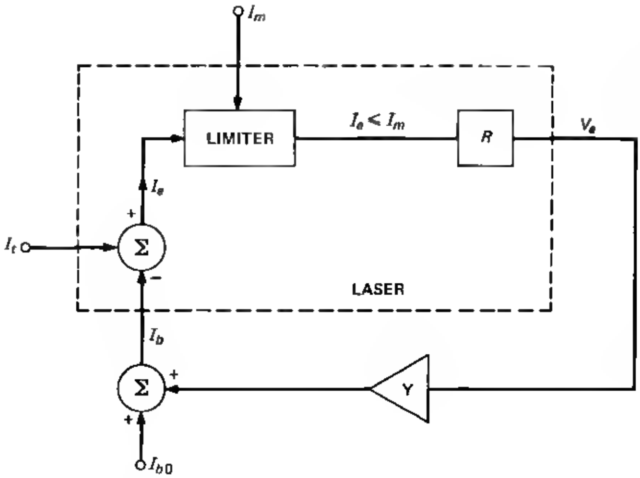

Fig. 4—System representation of the ABC circuit.

II. SYSTEM REPRESENTATION

In this section a mathematical model for the laser together with the ABC circuit is developed. This model is used to explain the function of the different parts needed to stahilize the laser output.

To analyze the operation of the ABC circuit, let us assume that the laser is hiased with a direct current I_b which is smaller than the threshold current level I_t. Then, according to Fig. 1, V_e can he expressed as a first-order approximation hy

$$V_e = \begin{cases} RI_e \text{ for } 0 \le I_e \le I_m \\ RI_m \text{ for } I_m \le I_e \end{cases} \tag{1}$$

where

$$R = \frac{dV_j}{dI}, \text{ evaluated at } I \approx I_t^-, \tag{2}$$

and

$$I_e = I_t - I_b. \tag{3}$$

The purpose of the ABC circuit is to minimize I_e, hy monitoring V_e to control I_b. Figure 4 shows a diagram of the ABC circuit and the laser. The laser is represented hy the hox indicated hy dashed lines. It has one output, V_e, and three inputs, I_m, I_t and I_b. In principle the ABC circuit is a transadmittance amplifier, with a gain Y, that amplifies and converts V_e into I_b:

$$I_b = I_{b0} + (Y \times V_e). \tag{4}$$

I_{b0} is a fixed prebias current, which is smaller than the minimum I_t; I_{b0} is optionally provided to reduce the current in the output transistor and gain required of the transadmittance amplifier.

Equations (1) through (4) determine the operating points of the laser to be:

$$I_b = I_t - \frac{I_t - I_{b0}}{1 + A} \quad \text{for} \quad 0 \leq \frac{I_t - I_{b0}}{1 + A} \leq I_m \tag{5}$$

and

$$I_e = \frac{I_t - I_{b0}}{1 + A}. \tag{6}$$

A is the closed-loop gain given by the product $R \times Y$. Equations (5) and (6) indicate that if $1 + A \gg (I_t - I_{b0})/I_m$ then

$$I_b \approx I_t \tag{5a}$$

and

$$I_m \gg I_e \approx 0, \tag{6a}$$

that is, the laser is biased at the laser threshold, the error current becomes small, and the modulating current is above the laser threshold.

III. INSTABILITY OF THE LASER OUTPUT

It will be assumed that the instability of the laser output is mainly caused by the variation of the laser threshold. The laser output power, L, produced by a fixed current I is

$$L = S(I - I_t) \tag{7}$$

where S is the differential quantum efficiency of the laser. Then tbe output instability is defined as:

$$U = \frac{dL}{dI_t} = -S. \tag{8}$$

When using the ABC circuit the laser has an additional bias current I_b, and in this case the power output is:

$$L_1 = S(I + I_b - I_t). \tag{9}$$

Then, according to Eq. (8), the instability of the laser driven by the ABC circuit is:

$$U_1 = \frac{dL_1}{dI_t} = -S\left(1 - \frac{dI_b}{dI_t}\right). \tag{10}$$

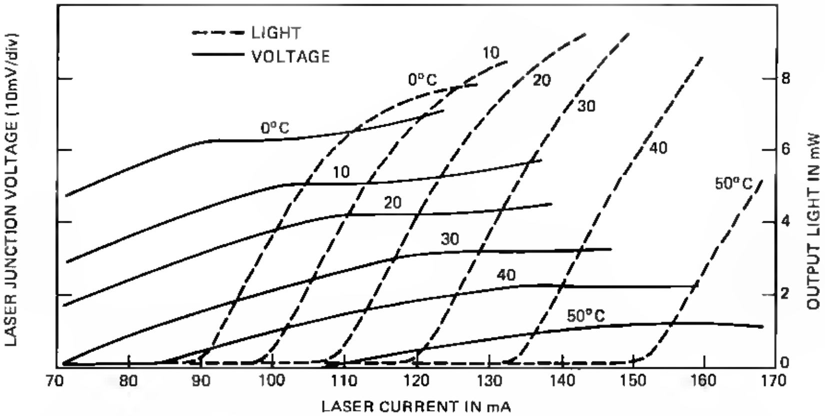

Fig. 5—Laser junction voltage and output light as a function of the bias current and the temperature.

Using Eq. (5) to calculate the derivative of I_b, one obtains

$$U_1 = \frac{-S}{A+1}. \tag{11}$$

The comparison of Eq. (11) with Eq. (8) indicates that, when the ABC circuit drives the laser, the instability of the laser output decreases $(A + 1)$ times, as would be expected for a closed-loop system of gain A.

IV. BIASING THE LASER BELOW THRESHOLD

This analysis has assumed so far that, above threshold, V_j is perfectly saturated and that V_e vanishes. This is not the physical case, because there is always a minimum V_e, called V_n, caused by the noise at the output of the operational amplifier and the lack of saturation of V_j (see Fig. 5). This deviation from the ideal situation requires one to limit the value of A such that

$$I_t - I_{b0} > \frac{A \times V_n}{R}; \tag{12}$$

otherwise the amplified noise will produce an $I_b > I_t$, and the circuit will overrespond to changes in V_e.

In order to be able to increase the value of A above that determined by eq. (12), a voltage ΔV is subtracted from V_e such that $\Delta V \gg V_n$. Then, the feedback loop increases I_b until $V_e = \Delta V$. $\Delta V \neq 0$ causes the laser to be biased below the threshold level. Figure 6 shows a diagram of the ABC similar to that of Fig. 4 but including ΔV. In this case, the new

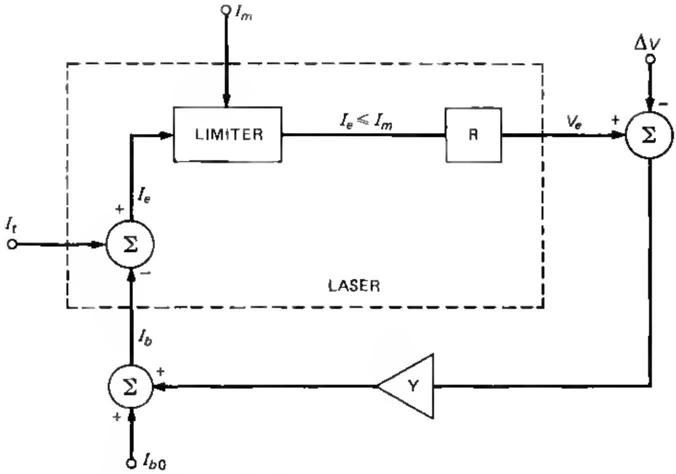

Fig. 6—System representation of the modified ABC circuit.

operating point of the laser is

$$I_e = \frac{I_t - I_{b0}}{A+1} + \frac{A}{A+1} \cdot \frac{\Delta V}{R}; \tag{13}$$

then for $A \gg \dfrac{(I_t - I_{b0})R}{\Delta V}$ and $A \gg 1$

$$I_e \approx \frac{\Delta V}{R} \tag{13a}$$

where $\Delta V > V_n$.

In eq. (13), ΔV is a constant but R is a function of I (see Fig. 7); R is the derivative of V_j, evaluated at a current below and near threshold. Because V_j is a logarithmic function of I,

$$R = \frac{dV_j}{dI} \approx \frac{V_T}{I_t} \tag{14}$$

where $V_T = nkT/q$. The constant n characterizes the semiconductor junction, k is the Boltzmann's constant, T is the junction temperature, and q is the electron charge.

By an analysis similar to that used for eq. (11), we can find a corrected value of the instability, using eqs. (14), (13), (3), (9), and (10). This new value, called U_2, considers the effect of having a $\Delta V \neq 0$:

$$U_2 = -S\left(\frac{1}{A+1} + \frac{A}{A+1} \cdot \frac{\Delta V}{V_T}\right). \tag{15}$$

The minimum and limiting value of U_2 is obtained by having an $A \gg 1$

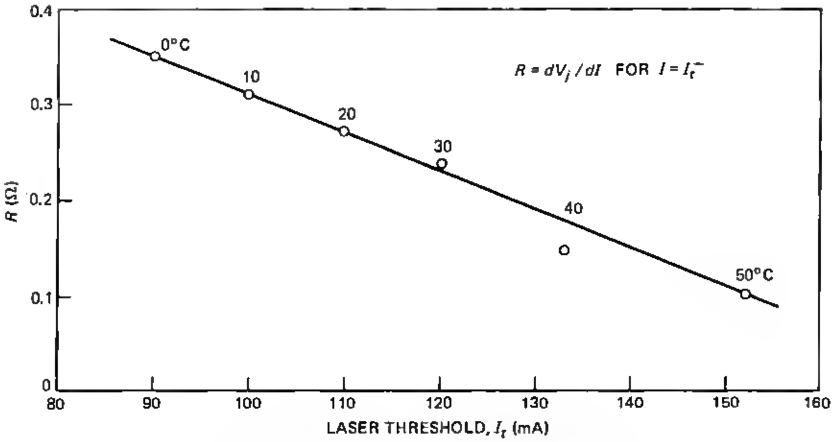

Fig. 7—R as a function of the laser threshold.

and $A \gg V_T/\Delta V$; then eq. (15) results:

$$U_2 \approx -S\frac{\Delta V}{V_T}. \tag{16}$$

According to eq. (16) the maximum improvement in the laser stability is determined by the ratio $V_T/\Delta V$. ΔV is caused by the nonsaturation of V_j, V_n. Figure 5 shows L and V_j as a function of I and T. At $L = 6$ mW and $T = 0°$C, V_n is less than 2 mV. Therefore one could make $\Delta V =$ 2 mV. V_T can be computed from the data in Fig. 7 using eq. (14), $V_T =$ 32 mV. For these values, one finds $V_T/\Delta V = 16$. According to eq. (15), $V_T/\Delta V$ determines the improvement in the laser instability caused by the ABC circuit.

V. ELECTRICAL CIRCUIT

The different parts of the ABC circuit are described in this section. As is shown in Fig. 2, the circuit consists of an operational amplifier, a peak detector, and a current source.

The operational amplifier has three functions: first, it determines V_j by compensating for the voltage drop in the laser series resistance; second, it filters the dc component of the junction voltage which depends on the laser temperature; and third, it amplifies the ac component to a value that can be processed by the envelope detector. In general, the bandwidth of the operational amplifier should be larger than the bandwidth of the modulating signal. This is required by the expression $AI_m \gg I_t - I_{b0}$, from eq. (5). But in certain cases, like that of video signals, one may use the synchronization signal to control the laser instead

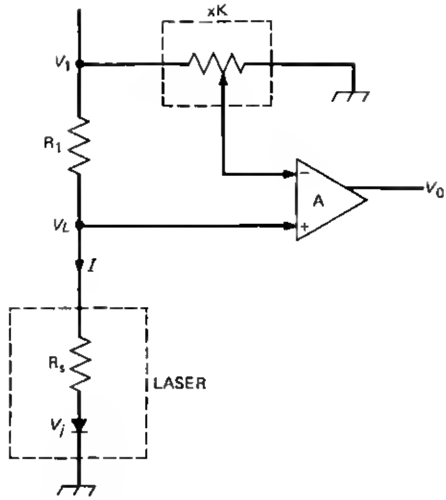

Fig. 8—Circuit to monitor the laser junction voltage.

of using the full bandwidth of the signal. In other cases one may add a low frequency signal for the ABC circuit.

Figure 8 shows a simplified portion of Fig. 2, with the two capacitors removed. The circuit was used to analyze the laser diode. It generates an output voltage V_o, which can be expressed in terms of V_j, the laser current I, the laser series resistance R_s, and other parameters of the circuit like the resistance R_1, the potentiometer ratio K, and the amplification A of the differential amplifier:

$$V_o = \{V_j(1 - K) + I[R_s - (R_s + R_1)K]\}A. \tag{17}$$

The circuit of Fig. 8, similar to a bridge circuit, compensates for the voltage drop across R_s by having K set to

$$K = \frac{R_s}{R_s + R_1} \tag{18}$$

which results in

$$V_o = \frac{A \times R_1}{R_1 + R_s} V_j \tag{19}$$

indicating that V_o is proportional to V_j. If a large A is desired, then the circuit should include an offset control to shift the output voltage so V_o is within the dynamic range of the amplifier. Figure 5 shows how the laser output light and V_o vary with I in the vicinity of threshold and at different temperatures of the laser. These data are useful to determine V_n; i.e., for $L = 6$ mW and $T = 0°$C, V_n is less than 2 mV.

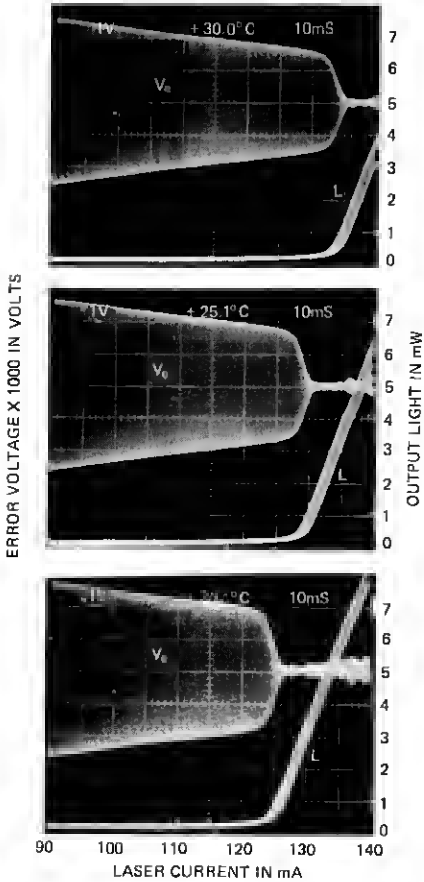

Fig. 9—Voltage at the output of the operational amplifier and laser output light as a function of the laser bias current at three different temperatures and without feedback connection.

In the circuit shown in Fig. 2, C_1 and C_2 remove the dc component of the input signal and the laser voltage, respectively; the potentiometer R_2 and the resistor R_1 compensate the voltage drop in R_s. The feedback resistor R_s determines the gain of the operational amplifier. Resistor R_4 sets the dc level of V_o, compensates the voltage drop across the diode D_1 and the emitter-base voltage of Q_1, and determines ΔV. In the circuit of Fig. 2, the peak output voltage is given by

$$V_o = \frac{R \times R_3}{R_s} \times I_e. \tag{20}$$

Figure 9 shows the open-loop output of the operational amplifier of Fig. 2 and the laser output light when the laser current is modulated by

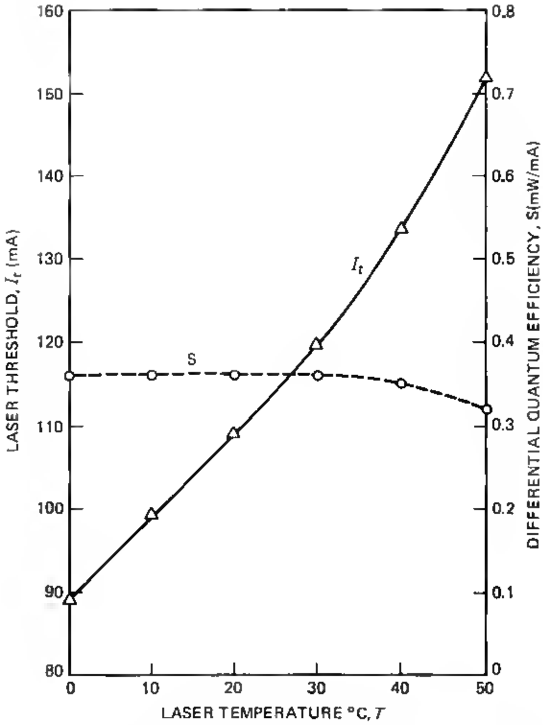

Fig. 10—Laser threshold and differential quantum efficiency as a function of the laser temperature.

a sinusoidal signal, as a function of the laser bias I_b at three different temperatures of the laser. The photographs clearly show that $V_e = V_n \approx 0$ for currents above threshold, and different laser temperatures.

The peak detector that determines the maximum error voltage consists of a rectifier and a low-pass filter. Different types may be used, and a simple one is shown in Fig. 2 which consists of a half-wave rectifier (D_1) and a low-pass filter formed by the capacitor C_3 and the input resistance of the current source.

The current source consists of an emitter-follower that converts the voltage from the peak detector into a current which is amplified by transistor Q_2. For the circuit of Fig. 2, the output of the current source is

$$I_b - I_{b0} = \frac{\beta_2 \times V_o}{R_5}, \tag{21}$$

where β_2 is the current amplification factor of Q_2. The peak output V_o of the operational amplifier $A1$ is given by eq. (20). According to Fig. 4,

one can define the current amplification A as

$$A = R \times Y = \frac{I_b - I_{b0}}{I_e} = \frac{\beta_2 \times R_3 \times R}{R_5 \times R_s}. \tag{22}$$

At room temperature, $I_t = 120$ mA, $R = 0.25\,\Omega$. $\beta_2 = 40$, $R_s = 2\,\Omega$, $R_3 = 100\,\Omega$ and $R_5 = 200\,\Omega$. One ohtains an amplification $A = 2500$. This amplification satisfies the condition of eq. (13a).

VI. DISCUSSION

An electronic circuit to improve the stahility of an injection laser was presented. Emphasis was placed on descrihing the fundamentals of the electronic feedhack rather than comparing its performance and limitations with other methods of intensity control.

The ABC circuit assumes that the laser junction voltage saturates ahove threshold, and it did not consider laser anomalies like kinks in the $L - I$ curve nor changes in the differential quantum efficiency, S.

The changes in S were neglected hecause they are less important than the changes in I_t produced hy temperature variation and age. This can he confirmed by looking at Fig. 10 which shows I_t and S as a function of the laser heat-sink temperature.

The circuit was operated with low-frequency signals helow 100 kHz, and no effort was made to improve the frequency response of the amplifier so the ABC circuit could be used to transmit analog or digital signals at frequencies larger than 100 kHz.

The circuit descrihed here may he useful to hias lasers near threshold during aging studies.

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